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Color Octet Contribution to J/ψ Photoproduction Asymmetries

G. Japaridze

Center for Theoretical Studies of Physical Systems, Clark Atlanta University, Atlanta, GA 30314, U.S.

W.-D. Nowak and A. Tkabladze†

DESY Zeuthen, D-15738, Zeuthen, Germany

Abstract

We investigate J/ψ photoproduction asymmetries in the framework of the NRQCD factorization approach. It is shown that the color octet contribution leads to large uncertainties in the predicted asymmetries which rules out the possibility to precisely measure the gluon polarization in the nucleon through this final state. For small values of the color octet parameters being compatible with J/ψ photoproduction data it appears possible that a measurement of J/ψ asymmetries could provide a new test for the NRQCD factorization approach, on one hand, or a measurement of the polarized gluon distribution from low inelasticity events ($z < 0.7$), on the other.

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†Alexander von Humboldt Fellow

1 Introduction

The study of double spin asymmetries in appropriate final states is a very promising way to measure the polarized gluon distribution function in the nucleon. The favored processes are those for which the involved production cross sections and subprocess asymmetries can be calculated in the framework of perturbative QCD and be predicted with small uncertainties. Recently, the measurement of J/ψ photoproduction asymmetries was suggested as a tool for direct access to the polarized gluon density [1, 2]; the analysis of asymmetries at the subprocess level was based on results obtained in the framework of the color singlet model (CSM) [3, 4]. However, the CSM can not be considered as a sufficiently reliable model to describe heavy quarkonium production and decay processes. The measured cross section of prompt J/ψ and ψ' production at large p_T at the Tevatron exceeds the CSM predictions by more than one order magnitude [5]. In photon-proton collisions, even after taking into account next-to-leading order corrections [6], the CSM does not describe satisfactorily different distributions in J/ψ production [7].

The factorization approach (FA) based on non-relativistic QCD (NRQCD) represents a more reliable framework to study heavy quarkonium production and decay processes [8]. In an extension of the CSM [3], the NRQCD FA implies that the heavy quarkonium can be produced through color octet quark-antiquark states, as well. The production of a heavy quark-antiquark pair can be calculated perturbatively because the hard scale is determined by the mass of heavy quark, whereas the evolution of the $(Q\bar{Q})$ pair to the final hadronic state is parameterized by nonperturbative matrix elements, $\langle \mathcal{O}_n^{\psi} \rangle$. The relative importance of the different intermediate states, both color octet and color singlet, is defined by velocity scaling rules [9]. The color singlet long distance parameters, being related to the quarkonium wave function at the origin, can be calculated in the framework of nonrelativistic models, while the color octet parameters have to be extracted from experimental data. Once this is done, predictions for other processes can be made. Unfortunately, the present-day theoretical uncertainties are still too large, preventing a determination of these parameters with enough accuracy to check the universality of the NRQCD FA [10]-[13].

In the framework of the color octet model the main contribution to J/ψ photoproduction is coming from the color octet states ${}^1S_0^{(8)}$ and ${}^3P_J^{(8)}$ [14, 15]. Throughout this paper we exploit the fact that the corresponding long distance matrix elements can not be determined separately from the prompt J/ψ production data at the Tevatron; it is only possible to extract their combination.

Spin effects in heavy quarkonium production, such as J/ψ [10, 16] and Υ polarization [17]-[20] in unpolarized experiments and spin asymmetries in hadroproduction [21, 22] can provide a possibility to check the NRQCD factorization approach. As ratios of cross sections, spin-dependent observables do not strongly depend neither on the mass of heavy quarks, nor on the factorization and renormalization scale. These parameters are crucial in the prediction of cross sections and they usually give rise to large uncertainties in the extraction of color octet parameters [10].

In the present paper we consider double spin asymmetries in J/ψ photoproduction in the framework of the NRQCD FA. We investigate the uncertainties depending on the long distance color octet parameters and the possibility to use J/ψ production asymmetries for a determination of the polarized gluon density. We will argue that a measurement of the polarized gluon density via double spin asymmetries in charmonium photoproduction can potentially provide an additional test of the NRQCD FA, or alternatively, the polarized gluon distribution can be measured once the FA is confirmed.

The deviation from the CSM prediction can also be used as a test of an alternative model

for heavy quarkonium production proposed by Hoyer and Peigne [23] which reduces to the CSM in the case of J/ψ photoproduction.

In the next section we consider J/ψ photoproduction and electroproduction asymmetries at the subprocess level. The uncertainties in the color octet long distance parameters are discussed in Sec. 3. The double spin asymmetries for various sets of long distance matrix elements and different parameterizations of polarized parton densities are calculated at $\sqrt{s} = 10$ GeV which can be considered as representative for both the HERMES and the COMPASS experiment [1, 2]. We also estimate the expected double spin asymmetries in J/ψ electroproduction for a possible polarized electron-proton collider with energy $\sqrt{s} = 25$ GeV [24].

2 Double Spin Asymmetries for J/ψ Subprocesses

2.1 J/ψ Photoproduction

The double-spin asymmetry A_{LL} for inclusive J/ψ photoproduction is defined as

$$A_{LL}^{J/\psi}(\gamma p) = \frac{d\sigma(\overrightarrow{\gamma} + \overrightarrow{p} \to J/\psi + X) - d\sigma(\overrightarrow{\gamma} + \overleftarrow{p} \to J/\psi + X)}{d\sigma(\overrightarrow{\gamma} + \overrightarrow{p} + \to J/\psi + X) + d\sigma(\overrightarrow{\gamma} + \overleftarrow{p} \to J/\psi + X)} = \frac{d\Delta\sigma/d^3p}{d\sigma/d^3p} \ , \tag{1}$$

where the arrows over γ and p denote the helicity projection on the direction of the corresponding momenta of the initial particles.

Throughout this paper we use the standard notation of spectroscopy to define the quantum numbers of intermediate quark-antiquark states, ${}^{(2S+1)}L_J^{(1,8)}$. Here S denotes the spin of quark-antiquark state, J is the total angular momentum, the superscripts (1) and (8) correspond to color singlet and color octet states respectively. The long distance parameter $\langle \mathcal{O}_{1,8}^H({}^{(2S+1)}L_J) \rangle$ describes the transition from the ${}^{(2S+1)}L_J^{(1,8)}$-state to a hadron H.

In lowest order of α_s only color octet states contribute to J/ψ production, namely through the following subprocesses:

$$\gamma + g \ \to \ {}^1S_0^{(8)} \ , \tag{2}$$
$$\gamma + g \ \to \ {}^3P_{0,2}^{(8)} \tag{3}$$

These heavy quarkonium states are produced at the kinematical endpoint in $2 \to 1$ subprocesses, i.e. at $z \simeq 1$, where $z = P_\psi \cdot P_p / P_\gamma P_p$. The double-spin asymmetries for these subprocesses were calculated in Ref. [22]. Uncontrolled uncertainties at $z \simeq 1$ arise from higher order terms in the NRQCD velocity expansion; in this particular case the higher order terms are enhanced by the kinematical factor $1/(1-z)$ which makes all predictions unreliable close to the kinematical boundary [12, 25]. In the same kinematics, the J/ψ is produced via the diffractive process, which is an additional source of uncertainty. Another kinematical characteristic of the $2 \to 1$ subprocesses, Eqs. (2)-(3), is the small transverse momentum of the produced J/ψ; the transverse momentum of the final hadronic state is determined mainly by internal motion of the colliding partons and by the recoil of emitted soft gluons in the hadronization phase.

All these uncertainties are smaller in J/ψ production at larger transverse momenta. The leading order contribution in this case comes from $2 \to 2$ subprocesses which are of the order of $\alpha\alpha_s^2$:

$$\gamma + g \ \to \ J/\psi + g \ , \tag{4}$$
$$\gamma + g(q) \ \to \ {}^1S_0^{(8)} + g(q), \tag{5}$$

$$\gamma + g(q) \rightarrow {}^3S_1^{(8)} + g(q), \tag{6}$$
$$\gamma + g(q) \rightarrow {}^3P_J^{(8)} + g(q). \tag{7}$$

The double spin asymmetries for J/ψ production in the framework of the CSM, whose corresponding subprocess is described by Eq. (4), were studied in Ref. [4]. We calculated the cross sections for the production of a color octet heavy quark-antiquark pair, Eqs. (5)-(7), for different helicity states of initial photon and gluon (quark). he expressions for $\Delta\sigma$ for photon-gluon subprocesses which give the dominant contribution to the J/ψ production are listed in the Appendix[1]. Our results after averaging the spins of the initial particles are in agreement with those used for the calculation of the J/ψ photoproduction cross section in the NRQCD FA [14][2].

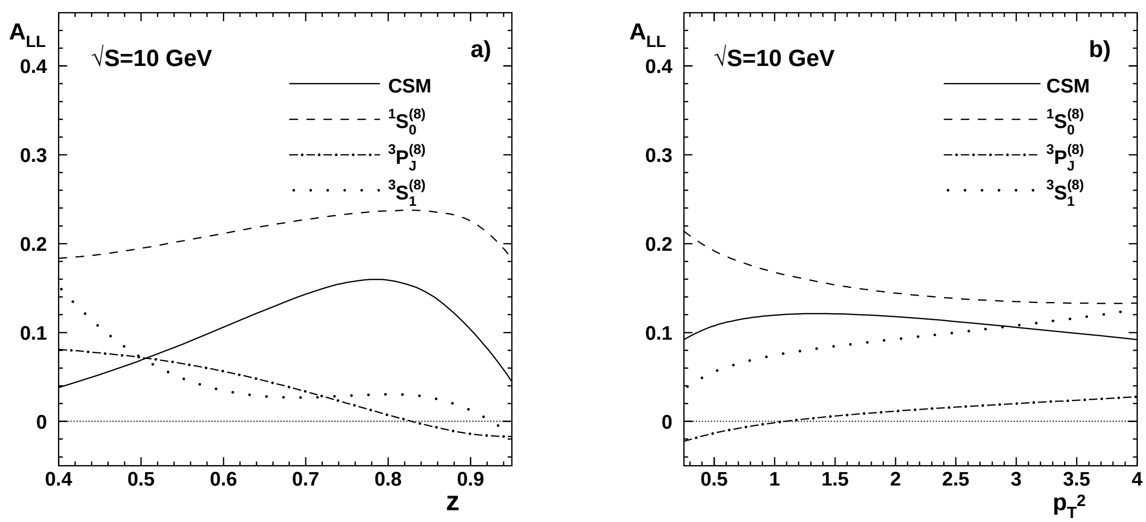

Figure 1: Different contributions to double spin asymmetries in quarkonium photoproduction, a) vs. z and b) vs. p_T, all for the GS LO parameterization (set A). The solid line corresponds to the color singlet ${}^3S_1$ state, the dashed line to the color octet ${}^1S_0^{(8)}$ state, the dash-dotted line to the color octet ${}^3P_J^{(8)}$ states and the dotted line to the color octet ${}^3S_1^{(8)}$ state.

The resulting double spin asymmetries for the photoproduction of various heavy quark-antiquark states at $\sqrt{s} = 10$ GeV are shown in Figs. 1(a) and 1(b). They are calculated for the Gehrmann-Stirling (GS) leading order (LO) parameterization (set A) of the polarized parton distribution functions (PDFs) [26]. For the unpolarized parton distribution functions the Glück-Reya-Vogt (GRV) LO parameterization evaluated at $Q^2 = p_T^2 + 4m_c^2$ was used [27]. As can be seen, the asymmetries for the ${}^1S_0^{(8)}$ (dashed lines) and ${}^3P_J^{(8)}$ (dash-dotted lines) octet states are rather different from the CSM prediction (solid line). Therefore, the predicted asymmetry for J/ψ production in the NRQCD FA is expected to be sensitive to long distance color octet parameters.

2.2 J/ψ Electroproduction

We also calculated the double spin asymmetries in heavy quarkonium electroproduction. The virtuality of the colliding photon can be used as an additional large scale in the process. Requiring

[1] The FORTRAN codes can be provided on request

[2] We are grateful to Michael Krämer for providing us with the analytical results for subprocess cross sections.

$Q^2 >> 4m_c^2$, some theoretical uncertainties connected with the enhancement of higher order corrections in the NRQCD expansion can be avoided. [12, 25]. At the same time it is possible to reduce the contribution from higher twist effects and from J/ψ diffractive production (for a detailed discussion see Ref. [25]).

In the framework of the CSM, J/ψ can be produced in electron-proton collisions only in order $\alpha^2\alpha_s^2$ subprocesses, $e+g \to e+(c\bar{c})+g$. The asymmetries for these subprocesses were calculated in Ref. [4]. However, the main contribution to the total J/ψ electroproduction cross section comes not from CSM, but from the leading order $\alpha^2\alpha_s$ subprocesses, similar to (2),(3), when color octet states can be produced only with small transverse momenta in the center-of-mass system of virtual photon and proton. In this paper we consider the double spin asymmetries only for these leading order subprocesses. The next-to-leading order color octet part, $O(\alpha^2\alpha_s^2)$, is even smaller than the color singlet model prediction [25] and does not significantly change the asymmetry calculated in the framework of the CSM in Ref. [4].

In the NRQCD factorization approach in leading order QCD J/ψ can be produced through two color octet states, ${}^1S_0$ and ${}^3P_J$. The expression for the corresponding cross section was obtained in Ref. [25]:

$$\begin{aligned}
\sigma(l+p \to l+J/\psi+X) &= \int \frac{dQ^2}{Q^2}\int dy \frac{G(x)}{yS}\,\frac{2\pi^2\alpha_s(\mu^2)\alpha^2 e_c^2}{m_c(Q^2+4m_c^2)} \\
&\times \left\{ \frac{1+(1-y)^2}{y} \times \left[\langle \mathcal{O}_8^{J/\psi}({}^1S_0)\rangle + \frac{3Q^2+28m_c^2}{Q^2+4m_c^2}\frac{\langle \mathcal{O}_8^{J/\psi}({}^3P_0)\rangle}{m_c^2} \right] \right. \\
&\left. - y\frac{32m_c^2Q^2}{(Q^2+4m_c^2)^2}\frac{\langle \mathcal{O}_8^{J/\psi}({}^3P_0)\rangle}{m_c^2} \right\},
\end{aligned} \tag{8}$$

where $G(x)$ is the gluon distribution in the proton, S is the invariant mass of the electron-proton system, and the momentum fraction of the struck parton is given by $x = (Q^2+4m_c^2)/yS$.

The corresponding polarized cross section has the form

$$\begin{aligned}
\Delta\sigma(l+p \to l+J/\psi+X) &= \frac{1}{2}(\sigma(\overrightarrow{l}\overrightarrow{p}) - \sigma(\overrightarrow{l}\overleftarrow{p})) = \\
&\int \frac{dQ^2}{Q^2}\int dy \frac{\Delta G(x)}{yS}\,\frac{2\pi^2\alpha_s(\mu^2)\alpha^2 e_c^2}{m_c(Q^2+4m_c^2)} \\
&\times \frac{1-(1-y)^2}{y}\left[\langle \mathcal{O}_8^{J/\psi}({}^1S_0)\rangle + \frac{3Q^4+8m_c^2Q^2-16m_c^4}{(Q^2+4m_c^2)^2}\frac{\langle \mathcal{O}_8^{J/\psi}({}^3P_0)\rangle}{m_c^2} \right],
\end{aligned} \tag{9}$$

where $\Delta G(x)$ is the polarized gluon distribution in the proton. The double spin asymmetry is defined by the ratio $A_{LL} = \Delta\sigma(lp)/\sigma(lp)$.

In the limit $Q^2 \to 0$ the expressions for the cross sections reduce to the convoluted photoproduction cross sections [14, 22] with polarized and unpolarized splitting functions correspondingly:

$$\lim_{Q^2\to 0}\sigma(l+p \to J/\psi+X) \;\to\; \frac{\alpha}{2\pi}\int \frac{dQ^2}{Q^2}\int dy \frac{1+(1-y)^2}{y}\hat{\sigma}(\gamma+P \to J/\psi+X), \tag{10}$$

$$\lim_{Q^2\to 0}\Delta\sigma(l+p \to J/\psi+X) \;\to\; \frac{\alpha}{2\pi}\int \frac{dQ^2}{Q^2}\int dy \frac{1-(1-y)^2}{y}\Delta\hat{\sigma}(\gamma+P \to J/\psi+X). \tag{11}$$

3 Matrix Elements and Results

In J/ψ photoproduction the dominant contribution comes from the color singlet state ${}^3S_1$ and the color octet states ${}^1S_0^{(8)}$ and ${}^3P_J^{(8)}$. The production cross section for the ${}^3S_1^{(8)}$ octet state is much smaller than the cross sections for these two octet states [14]. The color singlet matrix element is connected to the nonrelativistic wave function at the origin and can be evaluated in the framework of potential models. It can also be extracted from the leptonic decay width of the J/ψ. The corresponding color octet long distance matrix elements can not be calculated in perturbative QCD (pQCD) and are usually extracted from experimental data. For the color octet P-wave states they can be reduced to one parameter using the NRQCD spin symmetry relation:

$$\langle \mathcal{O}_8^H({}^3P_J)\rangle \;=\; (2J+1)\langle \mathcal{O}_8^H({}^3P_0)\rangle. \qquad (12)$$

After using these relations there are only two matrix elements left which give the main octet contribution to J/ψ photoproduction, $\langle \mathcal{O}_8^\psi({}^1S_0)\rangle$ and $\langle \mathcal{O}_8^\psi({}^3P_0)\rangle$. From the available data of prompt J/ψ production at the Tevatron it is only possible to extract the combination of these matrix elements with rather large uncertainties [28, 10, 13]. Apparently, at Tevatron energies the states ${}^1S_0^{(8)}$ and ${}^3P_J^{(8)}$ contribute significantly at small transverse momenta of J/ψ, $p_T < 5$ GeV. Consequently, the fitted value of the combination of matrix elements $\langle \mathcal{O}_8^\psi({}^1S_0)\rangle$ and $\langle \mathcal{O}_8^\psi({}^3P_0)\rangle$, defined as [13]

$$M_r^{J/\psi} \;=\; \langle \mathcal{O}_8^{J/\psi}({}^1S_0)\rangle + \frac{r\cdot\;\langle \mathcal{O}_8^{J/\psi}({}^3P_0)\rangle}{m_c^2}\;, \qquad (13)$$

is very sensitive to effects which change the p_T spectrum, such as dependence on factorization and/or renormalization scales, choice of parameterization of parton distribution functions etc. [10]. The number r is fitted from experimental data.

To test the sensitivity of double spin asymmetries on the color octet matrix elements we used two sets of parameters extracted from the Tevatron data on prompt J/ψ hadroproduction [13], as shown in Table I:

	LO	HO	scaling
$\langle \mathcal{O}_1^{J/\psi}({}^3S_1)\rangle$	$(7.63 \pm 0.54)\cdot 10^{-1}$ GeV^3	(1.30 ± 0.09) GeV^3	$[m_c^3 v^3]$
$\langle \mathcal{O}_8^{J/\psi}({}^3S_1)\rangle$	$(3.94 \pm 0.63)\cdot 10^{-3}$ GeV^3	$(2.73 \pm 0.45)\cdot 10^{-3}$ GeV^3	$[m_c^3 v^7]$
$M_r^{J/\psi}$	$(6.52 \pm 0.67)\cdot 10^{-2}$ GeV^3	$(5.72 \pm 1.84)\cdot 10^{-3}$ GeV^3	$[m_c^3 v^7]$
r	3.47	3.54	

Table I. Values of the long distance matrix elements from LO- and HO-improved fits to the CDF data.

The LO set of the matrix elements corresponds to the leading-order fit of the prompt J/ψ hadroproduction data at the Tevatron and the obtained value for $M_r^{J/\psi}$ is the largest among existing fits in the literature. These values of matrix elements lead to an increase of the photoproduction cross section as $z \to 1$ and dramatically overestimate the H1 and ZEUS data on J/ψ photoproduction at HERA.

When fitting the HO set, the higher-order corrections were taken into account only approximately by considering the initial and final state gluon radiation in the framework of a Monte Carlo simulation [29, 13]. Including effectively the primordial transverse momentum of partons

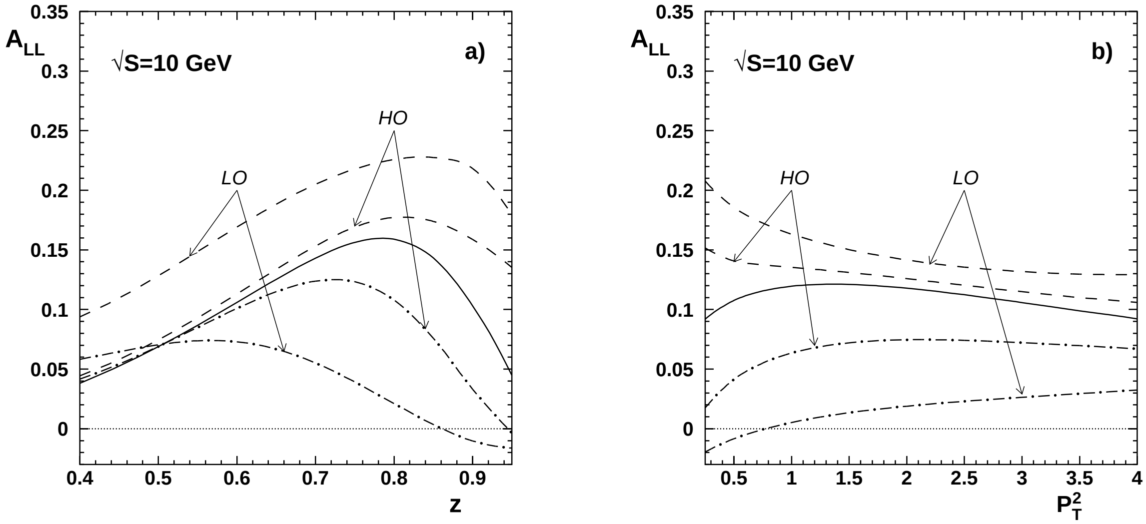

Figure 2: (a) z and (b) p_T dependence of double spin asymmetries of J/ψ photoproduction for LO and HO sets of color octet matrix elements. The solid curves correspond to the CSM prediction. The dashed curves correspond to the case when $\langle \mathcal{O}_8^{J/\psi}(^1P_0)\rangle = 0$, the dash-dotted ones to $\langle \mathcal{O}_8^{J/\psi}(^1S_0)\rangle = 0$.

increases the production cross sections of $^1S_0^{(8)}$ and $^3P_J^{(8)}$ color octet states at small values of p_T. The impact of this effect is a significant decrease of the $M_r^{J/\psi}$ combination by about one order of magnitude, as can be seen from table I. It is worth noting that this type of HO corrections changes the photoproduction cross sections for the color octet states only by about $20\% - 30\%$ at H1 and ZEUS energies [13]. The HO parameters, presented in Table I, are the smallest ones from the existing fits and are compatible with the H1 and ZEUS data on the z-distribution of the J/ψ *photo*production cross section. We consider this set as an example of small color octet parameters. The combination of color octet parameters $M_r^{J/\psi}$ was also extracted from fixed target *hadro*production data [11, 30] for $r = 7$, $M_7^{J/\psi} \simeq 2 \div 3 10^{-2}$ GeV^3. We note that these values lie in between the LO and HO sets of parameters, as given Table I, We used this range to check the sensitivity of the expected asymmetries on the model of J/ψ production.

In Fig. 2(a) and 2(b) the expected asymmetries in J/ψ photoproduction, calculated at $\sqrt{s} = 10$ GeV for the GS LO set A parameterization of polarized PDF's, are shown in dependence on z and p_T^2. As can be seen from these figures, the uncertainty in the asymmetry of J/ψ production is large for the LO set of color octet matrix elements because the values of $\langle \mathcal{O}_8^{J/\psi}(^1S_0)\rangle$ and $\langle \mathcal{O}_8^{J/\psi}(^3P_0)\rangle$ are not fixed separately but only as the combination (13). For the HO set the contribution to the cross section of the $^1S_0^{(8)}$ and $^3P_J^{(8)}$ color octet states is smaller, which reduces the deviation from the asymmetry predicted by the CSM especially for lower z-values ($z < 0.7$). To make a choice between the different sets of long distance parameters, more accurate measurements at energies lower than that for H1 and ZEUS are required in the future. The COMPASS experiment at CERN [2] and later possibly a presently discussed polarized electron-proton collider (EPIC) at $\sqrt{s} = 25$ GeV [24] will work at higher luminosities and may hence provide such measurements. The gluon polarization itself at that time has probably been measured in semi-inclusive reactions with less uncertainties, for example in open charm production at COMPASS or in dijet and direct photon production at RHIC [31]. If, in this situation, the HO set of parameters should fit the data of the lower energy experiments, the J/ψ photoproduction asymmetries can be used to test the NRQCD FA. Alternatively, based upon the HO set of parameters and relying on the NRQCD FA approach, the polarized gluon distribution can be

measured with acceptable theoretical uncertainties, if only J/ψ events with $z < 0.7$ will be used.

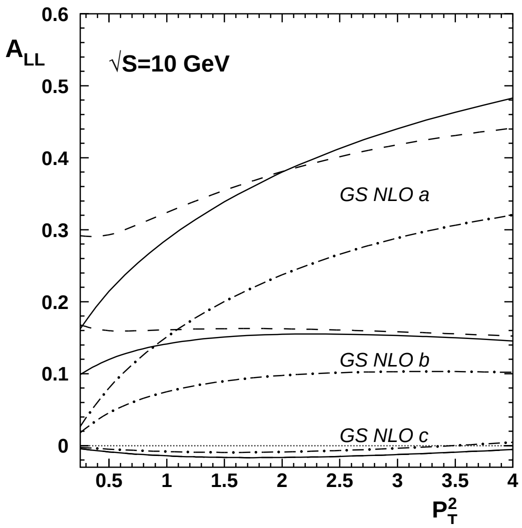

Figure 3: The double spin asymmetries for J/ψ photoproduction at $\sqrt{s} = 10$ GeV using HO long distance parameters versus p_T. The definition of lines is the same as in the previous figure.

Using the HO set of color octet parameters in Fig. 3 the double spin asymmetries for J/ψ photoproduction are presented at $\sqrt{s} = 10$ GeV for the different sets A, B, C of GS NLO parameterizations for polarized PDF's [26]. We used here different sets of NLO parameterization to show the sensitivity of the asymmetries to the polarized gluon distribution function, which is rather different for these three sets. We note that, as expected, the result for the GS LO set A parameterization is practically the same as for the GS NLO set B. We show only the p_T^2 dependence of the asymmetries. As was mentioned above, uncontrolled corrections are expected at large z from higher order terms in the velocity expansion because of ignoring the mass difference between the $(c\bar{c})$-pair and the final state hadron. This type of uncertainties can be neglected in the $d\sigma/dp_T$ distribution because the integration over z smears the singular region out [12, 25]. When using the HO set of color octet parameters, the p_T behaviour of the double spin asymmetry for J/ψ production is rather well described by the CSM prediction as long as color octet P states don't contribute, as can be seen from Fig. 3. If, in contrast, the color octet S-state does not contribute, the asymmetry decreases by about 30%. This behaviour appears for $p_T > 1$ GeV and seems to be rather independent of the actual NLO parameterization set used for polarized PDF's.

In J/ψ photoproduction experiments at low energy higher twist effects are expected to be suppressed by the heavy quark mass, which defines the hard scale of the corresponding subprocess, Λ_{QCD}/m_c. Moreover, it is not excluded that higher twist effects are suppressed even stronger by the transverse momentum of the produced quarkonium statee, or by factor $(m_{Q\bar{Q}}^2 + p_T^2)^{-1/2}$. A study of these effects may be performed at high luminosity experiments such as eN at DESY TeV Energy Superconductiong Linear Accelerator TESLA,[3] where enough statistics can be accumulated at larger values of transverse momentum.

In Fig. 4 electroproduction asymmetries are shown at $\sqrt{s} = 25$ versus photon virtuality Q^2, calculated using the 'largest' parameterization, namely GS NLO set A. As can be seen from this figure, the difference between the asymmetries for the color octet states $^1S_0^{(8)}$ and $^3P_J^{(8)}$ is large for a large gluon polarization offering a powerful tool to discriminate between the hitherto 'coupled' contributions from color octet S- and P-wave states. It is important to note that in leading order electroproduction large contributions from higher twist effects and diffractive J/ψ production are expected. They can be suppressed by requiring large enough $Q^2 >> 4m_c^2$ which leads, however, to a rapidly falling cross section and large statistical errors are expected [25]. It is a question of attainable statistics at EPIC whether it may be possible to achieve reasonable restrictions on the values of the color octet parameters from J/ψ electroproduction asymmetries. At high energies, $\sqrt{s} > 100$ GeV, which correspond to the polarized HERA option [33], the total

[3]A project of a high luminosity experiment scattering of TESLA electron beam off polarized nucleons is under consideration [32].

cross section is large but the asymmetries calculated with the commonly used parameterizations GS or Glück-Reya-Stratmann-Volgelsang (GRSV) [26, 34] are expected to be very small, less than 2%.

4 Conclusions

In the present paper double spin asymmetries in J/ψ photoproduction and electroproduction were studied in the NRQCD factorization approach. The asymmetries for the color octet states ${}^1S_0^{(8)}$ and ${}^3P_J^{(8)}$ which give the dominant octet contribution to the J/ψ *photo*production cross section, are significantly different from the CSM prediction. The values of the corresponding color octet long distance matrix elements can presently not be extracted separately from existing data on J/ψ hadroproduction. Two sets of long distance parameters were used to show the sensitivity of the expected asymmetries to this uncertainty. For the 'large' set of parameters extracted from CDF data [13] the asymmetries contain very large uncertainties. For the 'small' set of parameters, when higher order QCD corrections are partly taken into account, the predicted asymmetries for the two extreme choices of parameters are for $z < 0.7$ rather close to the CSM prediction. This 'small' set of long distance parameters is preferable to explain H1 and ZEUS data on inelastic J/ψ photoproduction. The planned high luminosity measurements at COMPASS and possibly at EPIC ($\sqrt{s} = 25$ GeV) may provide the possibility to fit the color octet parameters in *electro*production at lower energies with better accuracy. Here even a discrimination between S-wave and P-wave color octet states appears feasible because the CSM contribution is subleading in electroproduction. If the 'small' set of parameters should remain the prefered one, the J/ψ *photo*production asymmetries can be eventually used to test the NRQCD FA. Here it is anticipated that the gluon polarization will have been measured already with small uncertainties through other semi-inclusive modes in polarized electron-proton or proton-proton collisions. On the other hand, once the situation with the NRQCD FA has been clarified by other experiments, such as J/ψ and bottomonium polarization measurements, the measurement of double spin asymmetries in J/ψ *photo*production at HERMES and COMPASS can be used to extract the gluon polarization in the nucleon in LO pQCD using events in the range $0.4 < z < 0.7$, because for $z < 0.4$ the contribution of resolved photon subprocesses becomes essential.

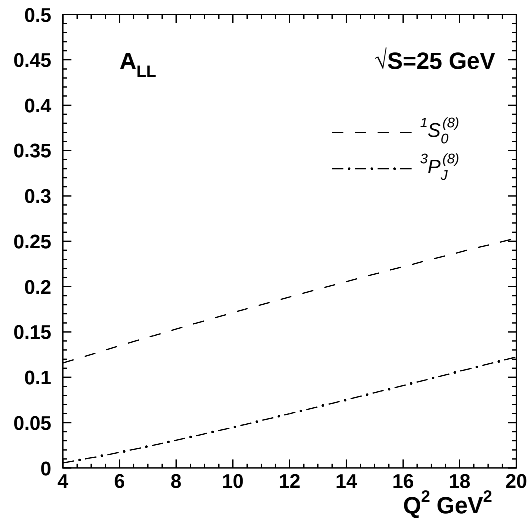

Figure 4: The Double spin asymmetries for J/ψ electroproduction at $\sqrt{s} = 25$ GeV for GS NLO (set a) parameterization. The dashed line corresponds to the asymmetry of ${}^1S_0^{(8)}$ state and dash-dotted line to the asymmetries of ${}^3P_J^{(8)}$ states.

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Appendix

Here we present the polarized cross sections for the production of $(c\bar{c})$ states in photon-gluon fusion subprocesses. The polarized cross section is defined as follows

$$\Delta\sigma \;=\; \frac{\sigma(++)-\sigma(+-)}{2}, \tag{A.1}$$

where the first and secod signs denote the helicity states of colliding photon and gluon, respectively. The expressions for unpolarized cross sections are listed in Ref. [15]. All cross sections were calculated for different helicity states of colliding particles. The obtained results were checked by comparing the unpolarized cross sections of this work, $(\sigma(++)+\sigma(+-))/2$, with those obtained in [14, 15]. As an additional check, we calculated the asymmetries for the production of scalar, ${}^1S_0^{(8)}$ and ${}^3P_0^{(8)}$, and tensor ${}^3P_0^{(8)}$ octet states in the limit $s \to M_{J/\psi}$ (i.e., at the threshold of quarkonium pair production). The subprocess level asymmetries for scalar and tensor states approach 1 and -1, respectively. The limit $4m_c^2 \to s$ implies that the emitted gluon in the $2 \to 2$ subprocess $\gamma g \to (c\bar{c})g$ becomes soft; the helicity properties of the amplitude then become the same as those of the amplitude of the $2 \to 1$ process $\gamma g \to (c\bar{c})$. It is easy to show that the asymmetries for the process $2 \to 1$ for scalar and tensor states are 1 and -1, respectively; the scalar(tensor) states are produced only in the case when the helicities of initial photon and gluon are $[++]([+-])$, which means that they have a total momentum projection $J_z = 0(\pm 2)$. The existence of such limits serves as an additional test for the analytical calculations of the polarized cross sections $\Delta\sigma$.

The spin dependent differential cross section for J/ψ production through a color singlet state has the form

$$\frac{\Delta\sigma(\gamma g \to J/\psi\; g)}{dt} = \frac{(ee_c g_s)^2 \langle \mathcal{O}_1^{J/\psi}({}^3S_1)\rangle}{16\pi s^2}\frac{32}{27Q^2}\{(st+tu+su)^2 - M^2 stu\}, \tag{A.2}$$

with $Q = (s+t)(s+u)(t+u)$.

For the case of an intermediate ${}^1S_0^{(8)}$ color octet state the corresponding cross section reads as

$$\frac{\Delta\sigma(\gamma g \to^1 S_0^{(8)} g \to J/\psi X)}{dt} = \frac{(ee_c g_s^2)^2 \langle \mathcal{O}_8^{J/\psi}({}^1S_0)\rangle}{16\pi M t Q^2} 3su(s^4 - t^4 - u^4 + M^8). \tag{A.3}$$

For J/ψ production through the color octet state ${}^3S_1^{(8)}$ the polarized cross section can be obtained from (A.2) by changing the long distance matrix element: $\langle \mathcal{O}^{J/\psi}({}^3S_1)\rangle \to 15/8\langle \mathcal{O}_8^{J/\psi}({}^3S_1)\rangle$.

Spin dependent cross sections for ${}^3P_J^{(8)}$ octet states have the form:

$$\begin{aligned}
\frac{\Delta\sigma(\gamma g \to^3 P_0^{(8)} g \to J/\psi X)}{dt} &= \frac{(ee_c g_s^2)^2 \langle \mathcal{O}_8^{J/\psi}({}^3P_0)\rangle}{\pi s^2 Q^3 t} 384\Big\{4M^6 s1^{-1} t^5 t_1 t_2 \\
&+ 4M^6 t^4 t_2 (3t - 2M^2) - M^2 s_1 t^3 (3t^4 + 2t^3 M^2 - 41 t^2 M^4 \\
&- 14tM^6 + 3M^8) - M^2 s s_1^2 t^3 (41t^2 - 118tM^2 + 68M^4) \\
&- M^2 s^2 s_1^2 t (73t^3 - 191t^2 M^2 + 139tM^4 - 45M^6) \\
&- 4M^2 s^3 s_1^2 t (19t^2 - 42tM^2 + 24M^4) - 9M^2 s^4 s_1^2 (5t^2 - 9tM^2 + 3M^4) \\
&- 12M^2 s^5 s_1^2 t - M^2 s_1^2 t^3 (14t^3 - 33t^2 M^2 - 22tM^4 + 3M^6) \\
&- s_1^2 t^2 (t^2 + ts + 2s^2) u_1^3 + 9M^{10} s^2 s_1 t + 18M^4 s s_1^2 (M^4 (t^2 + s^2) + s^4)\Big\}
\end{aligned} \tag{A.4}$$

$$\frac{\Delta\sigma(\gamma g \to^3 P_1^{(8)} g \to J/\psi X)}{dt} = \frac{(ee_c g_s^2)^2 \langle \mathcal{O}_8^{J/\psi}(^3P_1)\rangle}{\pi s^2 Q^3 t} 384 \Big\{ -4M^6 s_1^{-1} t^5 t_1 t_2$$
$$+ 4M^4 t^5 (t^2 - 3tM^2 + 6M^4) + 2M^2 s_1 t^4 t_2 (28M^4 + 5tt_1)$$
$$+ 2M^2 s s_1^2 t^3 (13t^2 + 20tM^2 + 3M^4) + 2M^2 s^2 s_1^2 t^2 (7t^2 + 11tM^2 - 2M^4)$$
$$+ 12M^2 s^3 s_1^2 t^2 u + 2M^2 s_1^2 t^4 (11t^2 + 16tM^2 + 23M^4)$$
$$- 4s_1^2 t^2 (t^2 + ts + 2s^2) u_1^3 + 8M^4 t^3 (M^4 s_1^2 + 2t^3 s_1 - M^6 u) \Big\} \qquad (A.5)$$

$$\frac{\Delta\sigma(\gamma g \to^3 P_2^{(8)} g \to J/\psi X)}{dt} = \frac{(ee_c g_s^2)^2 \langle \mathcal{O}_8^{J/\psi}(^3P_2)\rangle}{\pi s^2 Q^3 t} 128 \Big\{ 2M^6 s_1^{-1} t^5 t_1 t2$$
$$+ 2M^4 t^3 (3t^3 t2 + 10tt2M^4 - 12M^6 t_1) + M^2 s_1 t^4 (3t^3 + 20t^2 M^2$$
$$+ 85tM^4 + 52M^6) + M^2 s s_1^2 t^2 (11t^3 + 116t^2 M^2 - 55tM^4 + 48M^6)$$
$$+ M^2 s^2 s_1^2 t^2 (t + 2M^2)(13t + 11M^2) - 2M^2 s^3 s_1^2 t (t^2 + 39tM^2 - 48M^4)$$
$$- 6s^4 s_1^2 t M^2 (t + 14M^2) - 24 s_1^2 M^4 s^5$$
$$+ M^2 s_1^2 t^3 (5t^3 + 72t^2 M^2 + 53tM^4 + 12M^6)$$
$$- 2s_1^2 t^2 (t^2 + ts + 2s^2) u_1^3 + 12M^8 s^2 s_1 (2su + tM^2)$$
$$+ 36M^6 s_1 (M^4 t^3 + s^5 - s^4 M^2 + M^4 t^2 s) \Big\} \qquad (A.6)$$

The same process has been considered in another paper [35]. We note that our results for unpolarized and polarized cross sections for $^3P_0^{(8)}$ octet state production and for the spin dependent cross section of the $^3P_2^{(8)}$ octet state are different compared to Ref. [35]. However, our results for the sums of cross sections for P states, both polarized and unpolarized, were confirmed by those obtained in [35].

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